Understanding Coronal Heating and the Solar Spectral Irradiance

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1. Executive Summary

We propose an ambitious, forward leaning, comprehensive, and closely integrated research program to understand how the magnetically closed corona is heated to multi-million degree temperatures---one of the most important unsolved problems in space science. The scope of our investigation ranges from the interiors of individual current sheets to whole active regions and the global corona. Our approach is unprecedented in the way it interlinks MHD/kinetic simulations, field-aligned hydrodynamic simulations, imaging and spectroscopic observations, and hardware design. This requires a close-knit team with broad expertise, for which Goddard Space Flight Center (GSFC) is ideally suited. The ultimate goal of our interdisciplinary program is a state-of-the-art physics-based model of the solar spectral irradiance that will provide crucial input to models of the terrestrial upper atmosphere. Intermediate products include empirical measures of the spectral irradiance on timescales not yet characterized (< 81 days), and a numerical tool for incorporating magnetic reconnection onset conditions into MHD simulations.

2. Science Relevance, Goals, and Objectives

Understanding how the Sun's magnetically closed corona is heated to multi-million degree temperatures is one of the great unsolved problems in space science. The reason we are still seeking a satisfactory answer after eight decades since it was first posed is its extremely challenging nature. A comprehensive theory must not only describe a mechanism of sufficient strength, but must also explain the detailed spatial and temporal properties of the heating in a manner that satisfies a wide variety of observational constraints. This is an exceedingly tall order. No single "super simulation" can model the heating from first principles and make meaningful predictions of the resulting radiation signatures, because the competing demands are computationally too great. As a consequence, different aspects of the coronal heating problem have been treated largely in isolation, using different approaches. The challenge before us is to connect the different approaches, so that the knowledge gained from one is incorporated into the others in a way that finally enables a comprehensive, self-consistent, testable theory. The Heliophysics Science Division at GSFC has the necessary experts in all of the critical areas and therefore is ideally positioned to take on this challenge.

We study coronal heating for several reasons, not just because it is one of the great mysteries of nature. The processes involved, including magnetic reconnection and particle acceleration, are fundamental to many other phenomena---on the Sun, within planetary magnetospheres, and throughout the universe. **By understanding coronal heating, we will make progress on many other important problems.** There is also practical motivation. The solar spectral irradiance in the X-ray and EUV wavelength ranges is an important driver of space weather, controlling the structure, dynamics, and ionization state of the terrestrial upper atmosphere. Variations in the irradiance affect the propagation of radio signals and the drag experienced by space assets and space debris. Communication, navigation, and precision weapons guidance systems, as well as collision avoidance efforts, are all impacted. Variability on timescales of hours to days is due primarily to the evolution of solar active regions and their heating, and to the rotation of active regions onto and off of the visible solar disk. Characterizing this variability and better understanding its causes are two of our important objectives, which should **greatly enhance operational space weather capability**, as we will describe**.** Our work package is closely aligned with the Decadal Survey for Heliophysics, addressing two of its top-level goals: Goal 1. Determine the origins of the Sun's activity and predict the variations in the space environment, and Goal 4. Discover and characterize fundamental processes that occur both within the heliosphere and throughout the universe.

We will limit ourselves to the heating of the magnetically closed corona, where both ends of a field line are rooted in the photosphere. This includes active regions and the quiet Sun, which dominate the spectral irradiance. The heating of coronal holes and the solar wind is a separate, equally challenging problem that is beyond the scope of this investigation. So too are flares, which dominate the short time-scale variability. Evidence has accumulated that the magnetically closed corona is heated by small, impulsive energy bursts commonly called nanoflares (as reviewed, for example, in Klimchuk 2006, 2015, 2017)[1]. We have used this term generically in the past, noting that magnetic reconnection and waves both produce impulsive heating. Some of our research proposed here is "mechanism agnostic," applying equally to waves and reconnection, but much of it is specific to reconnection. This is not to suggest that wave heating is unimportant, but it simply cannot be included in an effort of this size.

As mentioned above, the coronal heating problem has traditionally been investigated with different, largely disconnected approaches. A major reason is the highly disparate spatial scales involved. The energy release process takes place at extremely thin current sheets in the corona. The creation of these sheets involves processes happening on much larger scales that are driven by flows at the solar surface. Most of the radiation that results, which is the basis of all diagnostics, comes not from directly heated plasma, but rather from plasma that has been "evaporated" into the corona from the chromosphere below. To accurately predict this emission requires an accurate treatment of the thin transition region interface between the corona and lower atmosphere.

Because of the competing requirements, only a subset of the important physics can be emphasized in any one study. Investigations have taken the form of: (1) observational studies; (2) field-aligned hydrodynamic models where the heating is specified in an *ad hoc* manner; (3) large-scale 3D MHD models of, e.g., active regions or the global corona, where the heating is either specified or computed from first principles, but with woefully inadequate spatial resolution, raising serious questions about the realism; (4) localized 3D MHD or kinetic models of individual current sheets, where the connections to larger scales and to the lower atmosphere are missing. These different approaches, each with their strengths and weaknesses, are highly complementary, yet they are almost always treated in isolation. **Breakthrough progress requires an integrated approach that examines all important aspects of the problem.** That is the hallmark of our work package. **Through carefully coordinated studies, we will achieve a comprehensive understanding of how active regions and the quiet Sun are heated, and how this heating determines the X-ray and EUV spectral irradiance.** We now describe the eight interlinked investigations that comprise our unique strategy.

[1] References supporting many of the statements made in this proposal are given in these three reviews. Due to space constraints, we limit the number of specific references cited here.

3. Methodology Including Data, Theory, and Models

3.1 Onset of magnetic reconnection: The coronal magnetic field is subdivided into an enormous number of elemental, topologically-distinct flux tubes, or strands. More than 100,000 of them exist in a single active region. Because their footpoints are randomly displaced by photospheric convection, the strands become twisted and tangled in the corona, and current sheets form at their boundaries. The stresses build until critical conditions are reached, the current sheets go unstable, and the field reconnects. It is vital to understand the onset conditions for reconnection, since they directly determine the magnitude of the energy release. If reconnection happens too soon, before the stresses have built to sufficient levels, the energy release is small. If it happens too late, the release is larger than observed. This is true not only of coronal heating, but also flares, CMEs, jets, magnetospheric substorms, and all other phenomena that involve the sudden release of built-up magnetic energy. Our results will therefore have widespread significance.

To simulate reconnection onset properly requires that the current sheet be adequately resolved, which implies an enormous number of computation cells. It is therefore not possible to include more than one or two current sheets in a given simulation. We have begun to study the tearing instability of a single current sheet representing the interface between two misaligned magnetic strands. Our initial simulations are quite idealized: triply periodic system, uniform coronal plasma, fixed rotation angle of the field across the sheet, and simplified energy equation. Even this situation is extremely difficult to model accurately. Reconnection begins with the tearing instability, which, under coronal conditions, is very fast even in sheets much thicker than the Sweet-Parker size (Pucci & Velli 2014). A resistive MHD treatment is therefore appropriate to study onset, since kinetic effects are not important (though see below). We are testing several well-known MHD codes to determine which is/are best suited for this problem: LaRe3D (Arber et al. 2001), ARMS (DeVore & Antiochos 2008), BATS-R-US (Toth et al. 2012), and HiFi (Glasser & Tang 2004). We are comparing the codes with each other and with the predictions of linear tearing theory (Baalrud et al. 2012). Figure 1 is an example of one of our runs, showing how "oblique tearing" causes inclined, twisted flux tubes to form inside the current sheet. Whether and how the tubes evolve to produce explosive energy release is something we will determine. Do they go kink unstable (Dahlburg et al. 2005)? Do they interact with each other in some complicated, turbulent manner (Huang & Bhattacharjee 2016)?

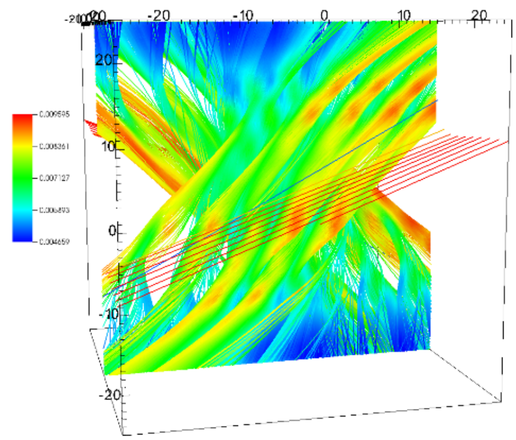

Fig. 1: Field lines in a tearing unstable current sheet simulated with BATS-R-US.

After fully understanding this simplest case, we will add increasing levels of complexity to achieve a highly realistic simulation of a current sheet extending from the top of the photosphere, through the chromosphere and transition region, into the corona. We will include optically thin radiation, parallel thermal conduction, and partial ionization (Leake & Linton 2013). Chromospheric energy balance will be treated in a simplified manner (e.g., Carlsson & Leenaarts 2012). The current sheet will be created by footpoint driving, considering both shear flows and converging flows to determine whether reconnection onset happens at a critical misalignment angle, critical sheet thickness, or something else. Our ultimate simulation will take into account the observed clumping of the magnetic field in the photosphere, which produces field lines that diverge with height. The vertical stratification of the field and plasma (and therefore the plasma β, Alfven speed, fractional ionization, etc.) is important for studying the height dependence of reconnection, which has important implications for thermal non-equilibrium, discussed below.

3.2 Multi-strand interactions: The simulations above will show us the conditions when reconnection sets in, but they cannot address what happens as the system responds to the resulting force imbalance and interacts with the surroundings. There can be a feedback associated with large-scale stresses. Other reconnections may be triggered as nearby current sheets are brought to their breaking point. Such collective behavior is important for understanding two important properties of nanoflares---their frequency of occurrence and their spatial distribution. If the delay between successive nanoflares on a given magnetic strand is much longer than a cooling time, the plasma cools fully before being reheated, and a wide range of temperatures are present. If the delay is much shorter than a cooling time, the temperature instead fluctuates about a nearly constant value. These extremes are called low-frequency and high-frequency heating, respectively. The spectrum of emitted radiation is vastly different in these two cases.

The corona consists of a diffuse component (that contains most of the plasma) and observationally distinct coronal loops. Evidently, a loop is produced when many nanoflares occur in near proximity over a short period of time. Thus, a loop is a bundle of thin strands heated by a "nanoflare storm." **A complete theory of coronal heating must explain the distribution of nanoflare frequencies and the existence of distinct loops.** This requires simulations of multiple magnetic strands and associated current sheets. We have performed such simulations using the ARMS code to investigate a process called helicity condensation (Knizhnik et al. 2015), and we are now turning our attention to nanoflare collective behavior. Figure 2 shows preliminary results. Beginning with a uniform field between two plates representing opposite polarity regions of the photosphere, we impose 200 random vortex flows. Flux tubes are produced with differing amounts of twist, so current sheets form at the boundaries between them. Nanoflares occur in the presence of continued driving. We do not solve a full energy equation, so the evolution of the plasma along the field is not treated accurately (no radiation, thermal conduction, or chromospheric evaporation). We have nonetheless devised a simple technique to account crudely for these effects that allows us to approximate the coronal emission. Figure 2 shows the EUV emission from a horizontal cut through the corona that would be detected by the Atmospheric Imaging Assembly (AIA) on the Solar Dynamics Observatory (SDO) using one of its intermediate temperature channels. The red (bright) patch on the left is suggestive of a nanoflare storm producing a coronal loop cross section. We will perform increasingly realistic simulations of this type, including driver flows that both twist and tangle the field, and we will employ a second code (e.g., LaRe3D) that more accurately simulates the emission. We will use a sophisticated cluster analysis technique (Uritsky et al. 2010, 2013) to quantify the spatial and temporal properties of both the heating and the emission.

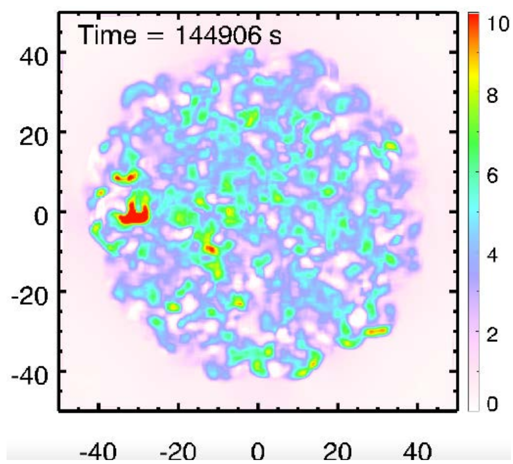

Fig. 2: Simulated AIA image from a multi-strand MHD simulation (color = intensity).

As emphasized in Section 3.1, the many current sheets in these multi-strand simulations are not adequately resolved, so reconnection may not begin under the right conditions and at the right time. This is the first example of how our different studies will be interlinked. We will use the knowledge gained from our simulations of individual current sheets to modify the multi-strand simulations. Although the exact procedure is yet to be determined, it will likely involve a numerical switch that turns on enhanced electrical resistivity when the correct local onset conditions are met. Such a technique has been used previously to model current-driven instabilities. We anticipate that this tool will be a great asset to the MHD modeling community and will be widely used.

<u>3.3 Thermal evolution:</u> The multi-strand simulations above predict a thermal evolution that depends sensitively on the heating frequency. This allows us to critically evaluate the simulations with actual observations. In a series of papers, we showed that virtually every line-of-sight through the corona intersects strands that are heated by low to intermediate-frequency nanoflares (Viall & Klimchuk 2011-17). To do this, we developed a novel technique that detects post-nanoflare cooling by measuring time lags in the intensity variations observed in different AIA channels. Emission in cool channels systematically lags emission in hot channels by a delay consistent with the expected plasma cooling time. It is remarkable that the technique works even when there are thousands of out-of-phase strands overlapping along the line-of-sight. An example is shown in Figure 3.

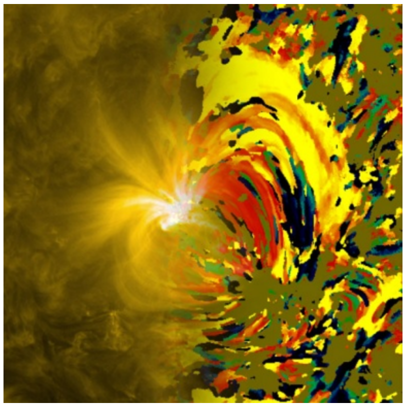

Fig. 3: Intensity in the 171 channel (left) transitioning to a map of cooling time (right) for an active region observed by AIA. Colors represent different time lags.

Our technique does not preclude the possibility that high-frequency nanoflares are also present along the same lines-of-sight as the lower frequency nanoflares. In fact, recent results based on the slopes of emission measure distributions suggest that nanoflares may occur with a broad distribution of frequencies. We will determine the relative proportions of low and high-frequency nanoflares by augmenting our analysis as follows. The time-lag technique works by cross correlating light curves with different amounts of imposed temporal offset and determining which offset maximizes the correlation coefficient. Photon noise introduces variability unrelated to plasma cooling, and by using the values of the coefficients together with the intensity fluctuation amplitudes, we will infer the relative numbers of low and high-frequency nanoflares. We will examine several different active regions, comparing the results with our multi-strand simulations.

<u>3.4 Thermal non-equilibrium:</u> The dynamic behavior discussed above is caused by highly time dependent heating, but such behavior can also result from steady heating if it is concentrated at sufficiently low altitudes in the corona. In that case, there is no solution to the static equilibrium equations. As the plasma "searches" for a nonexistent equilibrium, it undergoes periodic convulsions, typically involving the formation of a cold condensation. This is called thermal non-equilibrium (TNE) (Antiochos & Klimchuk 1991). It has been suggested that prominences correspond to collections of TNE condensations, and therefore they provide an ideal opportunity to study the height dependence of heating. We have previously used our 1D hydrodynamics code ARGOS (Antiochos et al. 1991) to simulate TNE in long, low-lying flux tubes appropriate to prominences (e.g., Karpen et al. 2006). We have recently begun to examine the AIA emission expected from such simulations and are finding that the time-lag maps have distinctive, evolving characteristics (Viall, Kucera, & Karpen, in preparation). We will continue this modeling effort and make quantitative comparisons with actual prominence observations. In addition to placing **important constraints on the vertical distribution of heating**, this comparison will constrain the nanoflare frequency, because TNE does not occur unless the frequency is sufficiently high. We will compare the results with the height and frequency predictions from our single current sheet and multi-strand MHD simulations.

Mikic et al. (2013) and we have found that TNE does not always involve the formation of a cold condensation. Instead, the plasma cools, but it reheats before the temperature drops much below 1 MK. If TNE of this type is a common occurrence (Downs et al. 2016), there should be widespread evidence for it in time-lag maps of active regions. Using ARGOS simulations, we will determine the time-lag signatures of TNE with incomplete condensations, just as we are doing for the cold condensations associated with prominences. We will compare predicted and observed time-lag maps to assess whether TNE is as common as has been proposed. In addition to the simulations, we will complete an ongoing theoretical investigation of the physical factors that control whether condensations are full or incomplete. Asymmetries in the heating rate and/or flux tube cross-sectional area are implicated. Differences that we may find between prominences and the rest of the corona, both in terms of plasma behavior and magnetic geometry, will provide important clues about the nature of the heating.

3.5 Reconnection dynamics: The observational tests of impulsive heating that we have discussed so far are largely indirect measures of the heating. At typical coronal temperatures of 1-4 MK, most of the observed emission comes not from directly heated plasma, but rather plasma that has been evaporated from the chromosphere due to thermal conduction and possibly energetic particles (see below). To diagnose the reconnection process in detail requires spectroscopic observations of plasma hotter than 7 MK. This directly heated plasma is both predicted and observed to be faint, but it is ubiquitous (Brosius et al. 2014), and has the advantage of not being contaminated by cooler evaporated plasma along the line-of-sight. We will determine the **spectral signatures of reconnection** by generating synthetic line profiles from our single current sheet simulations. The Doppler shifts, broadening, and especially the detailed shapes of the profiles contain important information about the reconnection dynamics (jets, plasmoids, turbulence, etc.). In addition to the resistive MHD simulations, we will perform particle-in-cell (PIC) kinetic simulations so that we can explore the details of the small regions where the field lines actually break. We will use the VPIC code (Bowers et al. 2008, 2009) and possibly also EPIC (Daldorff et al. 2014), which embeds a PIC domain within a larger MHD domain. Figure 4 shows a synthetic line profile from a very preliminary VPIC simulation of a tearing current sheet. More averaging in space and time is required to mimic a real observation. We will compare our predicted line profiles to observations of Fe XIX (592Å) and Fe XX (568Å) from the EUNIS rocket payload (Brosius et al. 2014) and Fe XXIII (264Å) from Hinode/EIS.

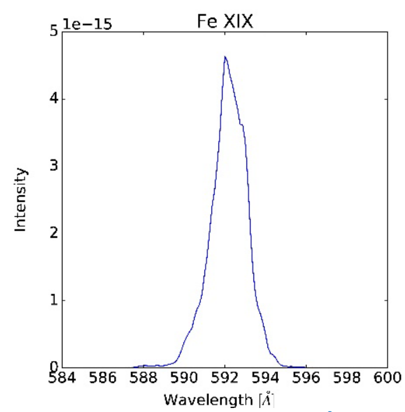

Fig. 4: Synthetic Fe XIX (592Å) line profile from a tearing unstable current sheet.

Looking toward the future, we will simulate a wide range of spectral lines to identify which provide the best diagnostics of reconnection. This will motivate the design of future instruments for missions like Solar-C or a possible Explorer. There are several wavelength regimes of interest (~10, ~100, ~1000 Å), but trade-offs must be evaluated with respect to sensitivity, spectral resolution, spatial resolution, and temperature coverage. The best way to make wise decisions about future hardware investments is through forward modeling: performing simulated observations based on the different options. The hardware, observation, and theory experts on our team will work closely together on this important activity.

<u>3.6 Particle acceleration:</u> Energetic particles are an important part of the energy budget of full-sized flares, but their role in nanoflares is largely unknown. To fully understand coronal heating, we much determine the relative contributions of energetic particles and bulk heating. Hard X-ray observations indicate that the number of highly non-thermal particles outside of flares is small, but mildly non-thermal particles are largely unconstrained because their emission tends to be overwhelmed by the thermal population. This is not true in the radio range, however, where type-III bursts trace energetic particle beams. These bursts drift rapidly in frequency as the beam propagates through a density gradient and produces emission at the local plasma frequency (Reid & Ratcliffe 2014). Large isolated bursts associated with flares are well observed in the corona and solar wind, with the particles escaping along open magnetic field lines into space. Do nanoflares also produce type-III bursts from particles traveling along closed field lines? To answer this question, we must contend with multiple overlapping events (a radio fuzz). Fortunately, our time-lag technique described in Section 3.3 was designed for precisely this situation. We simply need to correlate radio emission at different frequencies just as we correlated EUV emission in different AIA channels. The technique works for thousands of uncorrelated EUV cooling events, so it should work for thousands of uncorrelated type-III bursts. We have verified that observations at suitable frequency and cadence exist from the Very Large Array and Wilkinson Millimeter Array.

To quantitatively interpret our measurements, we need to understand how energetic particles propagate along magnetic strands. We will study this with simulations that combine a 1D hydro code with a Fokker-Planck particle transport code (Rubio Da Costa et al. 2015). In addition to predicting the type-III radio emission, we will predict the hard X-ray spectrum for comparison with data from the FOXSI sounding rocket, NuSTAR, and hopefully an eventual FOXSI SMEX, which will be more sensitive to possible nanoflare-accelerated particles. The details of the type-III and hard X-ray emissions will depend upon the initial energy spectrum and location of acceleration. Initially we will make reasonable assumptions, but ultimately the location (height) will be determined by our MHD and thermal non-equilibrium studies, and the energy spectrum will be determined by our PIC simulations, which track both thermal and non-thermal particles. Dahlin et al. (2015) have recently concluded that the efficiency of particle acceleration depends on the geometry of the reconnecting field, and since flares and nanoflares have different geometries, our study of nanoflare particle acceleration will provide an important test of the theory.

<u>3.7 Active region models:</u> An important long-range goal is to model solar active regions and the global corona in order to understand and predict the solar spectral irradiance---a critical input to the terrestrial upper atmosphere. Models of this type are not new, but they have been based almost exclusively on steady heating, which is an incomplete and possibly inaccurate description of the actual corona. The standard approach is to construct a "magnetic skeleton" by extrapolating from an observed photospheric magnetogram. This stationary field is then populated with plasma using field-aligned hydro models computed with an assumed (steady) heating (e.g., Warren & Winebarger 2006; Mok et al. 2016). We have recently helped to develop a powerful new tool, the GXsimulator (Nita et al. 2017), which uses this approach but has much more flexibility. The heating can take the form of nanoflares with magnitudes, durations, and frequencies that depend on physical parameters such as magnetic field strength, field line length, and footpoint position, in any way that the user chooses. Using the details of the heating obtained from our other studies, **we will construct the most realistic models of active regions thus far achieved**. We will test the models by comparing predicted and observed emissions, including, but not limited to, EUV, soft X-ray, and microwave images. The comparison will allow us to evaluate the adopted heating properties, providing crucial feedback to motivate the next generation of MHD simulations.

Figure 5 shows an example of an AIA 211Å image generated with the GXsimulator assuming low-frequency nanoflares. The randomly occurring nanoflares are assumed to have the same properties in the many sub-resolution strands that are assumed to pass through each voxel (3D pixel), but they vary from one voxel to the next, i.e., from one strand bundle to the next. Thus, only one time-averaged hydo simulation is needed for each bundle. For this example, we used our highly-efficient EBTEL code (Klimchuk et al. 2008; Cargill et al. 2012), which allows us to try many different combinations of heating parameters. More accurate but computationally intensive hydro codes like ARGOS and HYDRAD (Bradshaw & Cargill 2013) will be used for limited parameter sets and for situations that produce thermal non-equilibrium behavior. We will initially concentrate on active regions, since they dominate the spectral irradiance, but we will eventually expand our effort to global solar models. To test the models and the coronal heating on which they are based, we will compute disk integrated (or active region integrated) spectra for comparison with spectral irradiance data from SDO/EVE and TIMED/SEE. A very long-range goal is to drive the models with surface flows derived from time-dependent vector magnetogram data (Leake et al. 2017). In this way, we will predict what the spectral irradiance will be one or more days in the future. This capability is a **precursor to a physics-based operational space weather model.**

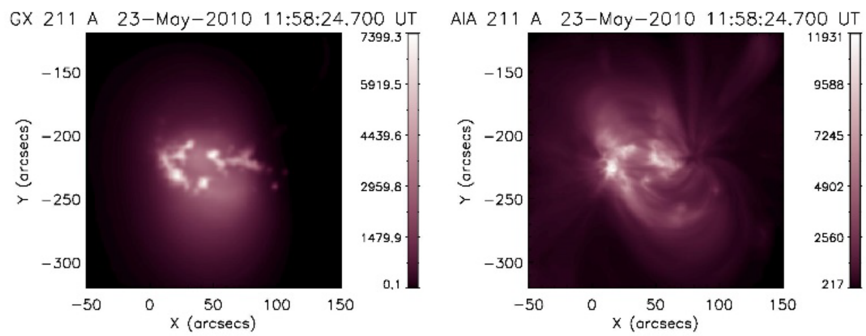

Fig. 5: Synthetic (left) and actual (right) images of an active region observed in the AIA 211Å channel.

3.8 Spectral irradiance variability: Variable EUV and X-ray emission produced by coronal heating strongly impacts the ionosophere-thermosphere-mesosphere (ITM) system by changing its ionization state, density, and temperature. While current ITM models can be driven by measured spectral irradiance information, proxies such as sunspot number or F10.7 (observed radiation at 10.7 cm) are typically used instead. These proxies are commonly averaged over periods ranging from 81 days to 1 year, losing much of the true variability of the solar input and limiting the utility of modeling efforts to understand the ionosphere. Additionally, the proxies capture only a small portion of the solar spectrum, and different parts of the spectrum, which are not necessarily well correlated, affect the atmosphere in different ways. As a consequence, the proxies have proven to be insufficient in quantifying the effects of solar driving throughout the solar cycle. Understanding this discrepancy is particularly important as the community moves toward real-time modeling applications.

To evaluate the implications of the evolving solar output for the ITM system, we will conduct the most comprehensive statistical study to date of the spectral irradiance on multi-day timescales using the SDO/EVE and TIMED/SEE datasets. We will compare the variability to both traditional proxies and more recently proposed proxies such as the MgII core-to-wing ratio. The power delivered to the thermosphere will be directly calculated by integrating the solar spectra over the photoionization cross-sections for the different atomic species (e.g., Richards et al, 1994), which will provide a calibration point for the previously used solar proxies. A long-term goal is to provide new measures of solar output to the operational community (both data-driven as described here and model-driven as described in Section 3.7). This work is especially timely given the upcoming GOLD mission, which will allow us to study the thermospheric response to variable solar input.

4. ISFM Relevance

4.1 Strategic Scope: Understanding coronal heating is **a holy grail of space science.** It is a primary objective of many past, present, and future NASA missions. However, never before has the problem been attacked with such an **ambitious, forward leaning, comprehensive, and closely integrated approach** as we propose here. The interlinkage among MHD/kinetic simulations, field-aligned hydro simulations, imaging and spectroscopic observations, and hardware design is unprecedented. Our scope ranges from the interiors of individual current sheets to whole active regions and the global corona. The approach is unique in the way knowledge gained from one study directly influences the design, execution, and interpretation of other studies. As but one example, consider the following chain. MHD simulations of individual current sheets will reveal the onset conditions for magnetic reconnection. These onset conditions will be incorporated into MHD simulations of multi-strand systems to determine the frequency and other properties of nanoflares. This sets the heating for field-aligned hydro simulations that will accurately compute the resulting radiation, taking full account of the coupling between the corona, transition region, and chromosphere. Finally, the hydro simulations will be used to populate flux tubes with plasma in active region and global corona models, from which we will determine the solar spectral irradiance. Along the way, we will answer such critical questions as: What are the relative proportions of low-frequency and high-frequency (quasi-steady) heating? How are observationally distinct coronal loops produced, as compared to the diffuse corona? What is the altitude distribution of coronal heating, and how common is thermal non-equilibrium? Do nanoflares produce energetic particles, and if so, what is their role in the energy budget? What are the spectroscopic signatures of reconnection, and what is the optimum design of future instruments that maximizes their diagnostic capability?

The inter-disciplinary nature of our research program and its relevance for applied space weather prediction are two other reasons why it is appropriate for the ISFM. The solar spectral irradiance is an important driver of the ITM system. We will study observed irradiance variability on timescales < 81 days, which is at present largely uncharacterized, and we will develop the physical understanding of how this evolving emission is produced. This will be excellent preparation for the upcoming Global Dynamics Constellation strategic mission.

<u>4.2 Why Goddard?</u> Our ambitious program requires experts in many different areas, and these experts must be in close physical proximity to facilitate the coordination and face-to-face interaction that are necessary for success. Goddard is the only organization in the world where all of the required team members are co-located. Two of our members have recently left Goddard, but are just "down the street" (Lars Daldorff is at APL/JHU and Kalman Knizhnik is at NRL). They still have offices as Goddard and visit regularly.

<u>4.3 Community Service:</u> The coronal heating problem is so important that breakthrough progress of the type we expect must be considered a service to the community. If successful, the knowledge gained will surely have a major influence on the future research of many others throughout the world. There are also more tangible products that will come from our work. The proposed interconnected studies will culminate in a state-of-the-art, physics-based model for the solar spectral irradiance, which we expect will eventually transition to an operational model with predictive capability. The model will be delivered to the Community Coordinated Modeling Center (CCMC) at Goddard. The GXsimulator (with steady coronal heating) is already available to the community through SolarSoft, and all of our proposed improvements will be incorporated into this open version. The new empirical measures of spectral irradiance variability on time scales not previously characterized will be of immediate value to the research and operational communities. The onset conditions for magnetic reconnection that we will determine will impact the interpretation of many phenomena that involve the explosive release of magnetic energy (CMEs, jets, substorms, etc.). Our numerical tool for incorporating these onset conditions into MHD simulations will be made available to and, we expect, heavily used by the broader heliophysics, astrophysics, plasma physics, and fusion communities. One member of our team, Sherry Chhabra, will be trained under our program and earn her PhD from the New Jersey Institute of Technology.

5. Plan of Work and Management Structure

Although all of our studies are interconnected, we will make significant progress on each of them in parallel. For example, our multi-strand MHD simulations will make use of the reconnection onset tool when it is available, but in the meantime we will learn a great deal about how different strands interact and produce nanoflare storms. The simulations will be repeated when the tool is ready, and differences will be studied. This will provide useful information for reinterpreting previously published MHD models that do not treat reconnection onset properly.

The active region models discussed in Section 3.7 are another example of how intermediate progress can be made. Before the detailed properties of coronal heating are established from the other studies, we will consider a variety of *ad hoc* heating parameterizations to find which set best reproduces the observations. Of course the parameterized and physics-based heating must ultimately agree, and any initial discrepancies will provide valuable feedback, leading to a deeper understanding.

A final example concerns our study of particle acceleration and transport and the production of type-III bursts described in Section 3.6. We will ultimately use the energetic particle spectrum obtained from our kinetic PIC simulations, but initial progress can be made by assuming one or more plausible spectra.

Although individual studies will proceed initially in parallel, we will coordinate to the maximum possible degree at all times. Lack of coordination has been one of the shortcomings of the coronal heating community and has limited progress. It is time for a change! To facilitate coordination, we will hold regular team meetings where results from the individual studies will be shared and discussed by all. Team members will be encouraged to take a big picture view, even as they concentrate on their particular piece of the puzzle. The primary roles of each member are listed succinctly below.

James Klimchuk (Team Leader) will oversee the program and ensure that all the studies are closely coordinated. He will play an active role in all of them, including design, implementation, and interpretation. He has extensive background in hydro modeling, MHD modeling, and observations, and he has a broad understanding of the coronal heating problem, having been the keynote speaker at the last two major meetings devoted exclusively to the topic (Klimchuk 2006, 2015).

James Leake (Deputy Team Leader) will assist Klimchuk in ensuring coordination and play key roles in the studies of reconnection onset and multi-strand interaction.

Joel Allred will model the propagation of energetic particles along coronal strands for predicting type-III radio emission and hard X-ray emission associated with nanoflares.

Spiro Antiochos will provide insight on all aspects of the program, but especially the multi-strand MHD modeling effort.

Jeffrey Brosius will lead the observational study of EUV spectral lines for comparison with reconnection simulations.

Sherry Chhabra will lead the study of type-III radio bursts (the basis of her PhD dissertation).

Lars Daldorff will play a key role in the study of reconnection onset and lead the PIC/kinetic study of reconnection signatures and particle acceleration.

Adrian Daw will lead the study of future instrumentation.

Judith Karpen will model thermal non-equilibrium, both within and outside of prominences.

Jeffrey Klenzing will lead the spectral irradiance study and be the team’s vital link to the ITM community.

Kalman Knizhnik will lead the study of multi-strand interactions.

Therese Kucera will lead the observational study of prominences and help with the GXsimulator comparisons.

Nicholeen Viall will lead the time-lag studies of nanoflare frequency and thermal non-equilibrium outside of prominences, and play a key role in modeling active regions using the GXsimulator.

Vadim Uritsky will analyze the spatial and temporal properties of the heating in the multi-strand MHD simulations.

6. Annual Milestones and Deliverables

The ISFM encourages ambitious, forward leaning, longer-term, higher-risk research that is not amenable to the same time-stamped milestones and deliverables that might apply to traditional R&A programs. The goals we have set are realistic, but many of them will not be achieved within three years. We hope to be evaluated on the progress made, which includes overcoming hurdles that are not always easy to anticipate. In this regard, we have been humbled by the challenges we have already experienced in simulating the tearing of a seemingly simple current sheet with a guide field. Our code comparison is a first, as far as we are aware, and the disagreements we have found have been eye opening. Reconnection onset is a highly challenging yet fundamentally important problem, and is a perfect example of the type of work that should be supported by ISFM. With this caveat in mind, we provide the following timetable for expected progress.

Year 1: Select code(s) for reconnection onset study. Simulate static (undriven) current sheets with different thicknesses and different shear in a uniform coronal plasma. Simulate a multi-strand system driven by vortex flows and compute statistics on the spatial and temporal properties of the heating. Select prominences and measure their time lags with SDO/AIA observations. Develop an analytical theory of thermal non-equilibrium, distinguishing partial and complete condensations, and test the theory with hydro simulations. Perform PIC simulations of reconnection. Use simple models to evaluate the feasibility of detecting overlapping type-III bursts from nanoflares. Look for type-III bursts in real data. Begin to study EUV spectral irradiance variability on time scales shorter than 81 days.

Year 2: Simulate current sheets driven with converging and shear flows in a uniform coronal plasma. Simulate static (undriven) current sheets with different thicknesses and shear in a stratified chromosphere-corona system. Study the detailed interaction of two twisted magnetic strands. Determine the proportions of low and high-frequency nanoflares using the "augmented" time-lag approach. Measure time lags in simulated SDO/AIA observations of thermal non-equilibrium with partial and complete condensations and compare with actual observations. Generate synthetic EUV spectral line profiles from PIC and MHD simulations and compare with observations. Begin to develop new instrument concepts based on simulation results. Perform sophisticated simulations of energetic particle transport in loops to better interpret the type-III measurements. Compare EUV spectral irradiance variability with current proxies and begin to develop new data-driven measures for input to terrestrial models. Use the GXsimulator with parameterized heating to model active regions and compare with observations.

Year 3: Simulate current sheets driven with converging and shear flows in a stratified chromosphere-corona system. Begin to develop a tool for incorporating reconnection onset conditions into MHD codes. Simulate a multi-strand system driven by random transverse flows and compute statistics on the spatial and temporal properties of the heating. Determine the spectrum of energetic particles from PIC simulations of reconnection and use as input to improved type-III simulations. Generate synthetic hard X-ray spectra and compare with observations. Make improved GXsimulator models of active regions using information gained from other studies and compare with imaging and spectral irradiance observations. Compare the new spectral irradiance measures with the thermospheric response seen by GOLD. Continue unfinished work started in years 2 and 3.

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